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4T CMOS Image Sensor Pixel Degradation due to X-ray Radiation

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***Abstract*--This paper presents a radiation study on the pinned photodiode (PPD) and Transfer Gate (TG) of 4T (4 Transistor) CMOS Image Sensors (CIS). The PPD and the TG are the most sensitive elements for the sensor's dark signal. The transfer gate length has an effect on the dark current due to the electric field variation in the transfer channel and the defect generation near the overlap region between PPD and TG. The low value of the TG clock signal is also evaluated for its influence on the dark signal. Meanwhile, the dimensional effect of the PPD and TG before and after radiation is demonstrated as well, which shows different results from 3T pixel.**

I. INTRODUCTION

CMOS Image sensors (CIS) are nowadays getting more preferable due to the improving image quality. For example, by employing pinned photodiode (PPD) in 4T pixel, the critical pixel parameter, dark current, is largely reduced to a low level comparable to that one of CCD[1]-[3]. Therefore, 4T CIS is being widely applied in the space/medical field to grab a low-dark-current image instead of 3T pixel, where radiation has strong negative influence on image quality. However, the pinned photodiode and transfer gate in the 4T pixel make its readout operation and dark current sources more complicated and different from its 3T opponent[2]. The main dark current contribution from the depletion of the photodiode edge at the surface in 3T pixel case cannot be considered on 4T anymore when radiation issues are concerned[4]. The transfer gate as an extra transistor has been reported as an additional dark current source[5]. Moreover, radiation induced interface trap generation and shallow trench isolation (STI) oxide trapped charges are also responsible for the sensor dark signal increase[6][7]. Therefore, this work is going to detail the radiation induced degradation behavior of the PPD and TG areas concerning pinning voltage and dark electrons (dark current). The evaluated pixels in this work have 4 different TG lengths (gate length), 5 different PPD lengths (in the direction of gate length) and each type of pixel has an array size of 6×4. The sensors are irradiated to 30krad and 60krad by X-Rays with an average energy of 46.2keV.

II. RESULTS AND DISCUSSION

Figure 1 illustrates a 4T pixel schematic with a cross section of the PPD and TG, and the timing for conventional readout and pinning voltage measurement.

The 4T pixel is composed of a PPD, a TG, a reset transistor (RST), a row selector transistor (RS) and a source follower (SF).

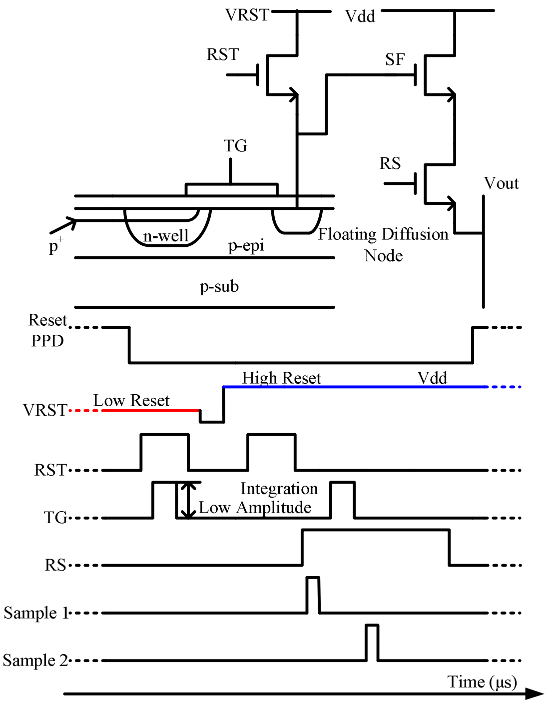

Figure 1. Pixel schematic and readout timing

The VRST is manipulated by sweeping and switching from a low value to a high one to measure the pinning voltage. During the conventional readout, it is connected to Vdd. The low value of the TG clock is used to modify the electrical stress under its channel and nearby the overlap region between the PPD and TG, where a high electric field exists, in order to bring the TG-gate-induced dark current down after radiation[8].

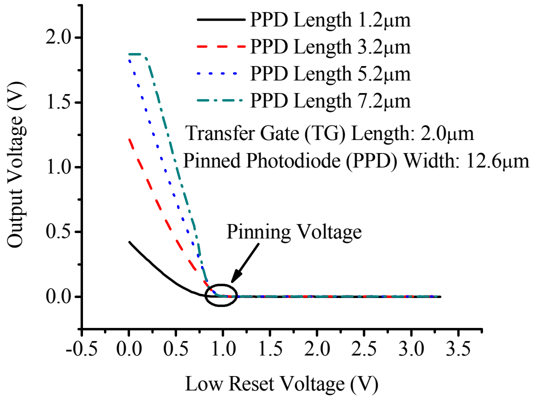

Figure 2. Pinning voltage measurements with different PPD length

Figure 2 shows the sensor's output voltage as a function of the low reset voltage on VRST. This measurement is a tool for extracting the pinning voltage. The low reset voltage is used to allow the PPD to accept a certain amount of charges within the range of its pinning voltage, which then can be read out by a conventional timing through connecting VRST to Vdd. As soon as the low reset voltage reaches a value higher than the PPD pinning voltage, the PPD will not get charges from VRST anymore and the sensor's output voltage remains low. That knee voltage shown in Fig.2 then equals to the pinning voltage. It is also shown in Fig.2 that when the low reset voltage is 0V, a smaller PPD has a smaller output voltage since it has a lower charge capacity. However, the pinning voltage is independent of the PPD size, while fully dependent on its doping profile and depletion region[2][9].

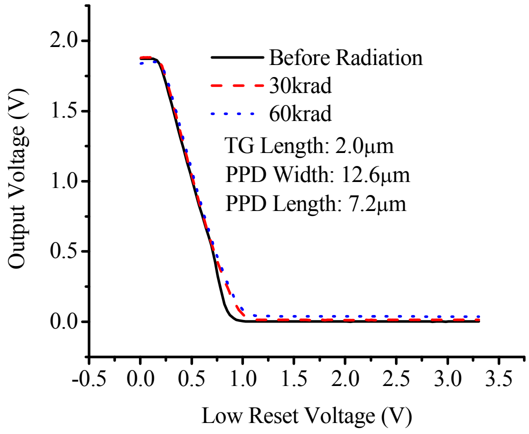

Figure 3. Pinning voltage measurement of a certain pixel with radiation doses

Figure 3 shows the post-irradiation output voltage of one pixel type as a function of the low reset voltage. It shows no variation of pinning voltage after radiation. Therefore, the shallow surface and bulk depletion regions of the PPD are not largely expanded by the increasing trapped charges in the surrounding STI oxide induced by radiation. Meanwhile, the PPD depletion region is mainly determined by a lower depletion region of n-well/p-epi due to the doping profile, which is deeper than STI. Thus, the radiation has less effect on the pinning voltage. However, when the low reset voltage exceeds the pinning voltage value, the pixel output voltage slightly goes up with the radiation doses, which can be attributed to the radiation induced dark current increase from the PPD because the VRST does not introduce any extra charges.

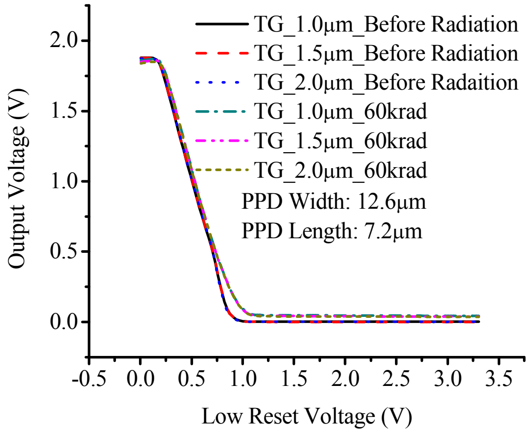

Figure 4. Pinning voltage measurements with the variation of TG length and radiation doses

Figure 4 shows the TG length effect on the pinning voltage measurement and its dark signal before and after radiation. It proves that the PPD pinning voltage is not correlated with TG length at all. Furthermore, after 60krad, the post-irradiation output voltage is not influenced by TG lengths neither when measured with VRST larger than the pinning voltage. Thus, it can be further confirmed that a tiny post-irradiation increase of the output voltage is mostly from the PPD dark current, which also shows that the effect of PPD on pixel dark current is small in 4T CIS after radiation.

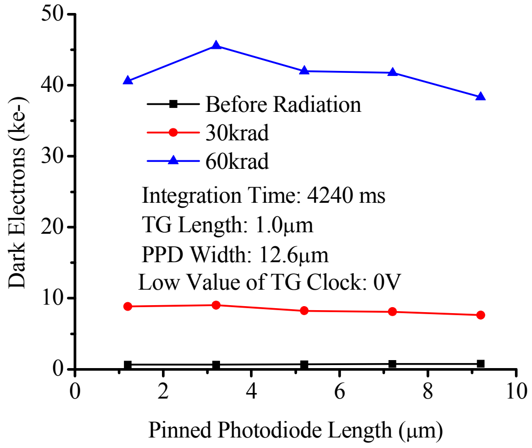

Figure 5. Pinned photodiode length effect on dark electrons with radiation doses

Based on the above results of the PPD pinning voltage and pixel output voltage, in Figure 5, the pixel dark signal measurement is shown for different sizes of the PPD in terms of electrons before and after radiation with an integration time of 4240ms. Since the photodiode surface is pinned by a highly doped p layer, the surface p-n junction depletion region (usually existing in 3T pixel) is eliminated in a 4T pixel. This kind of perimeter dependent surface depletion region is proved to be a main dark current source for photodiode where the surface recombination and thermal generation contribute a lot to the dark current[4][7]. However, in 4T pixel this dimensional effect is greatly reduced. Meanwhile, there is no dark current originating from the depletion region expansion induced by post-irradiation trapped charges due to the surface p-n junction which can have more defect generation[6]. Thus, as for a 4T pixel, the post-irradiation increase of dark signal is not determined by the PPD perimeter anymore which is shown above because there is no contact between the interface and a depletion region. Meanwhile, as shown in Fig. 5 after radiation, the pixel shows an obviously absolute increase of dark signal with radiation doses, however, the PPD length effect is not dominant.

Figure 6 presents the pixel dark signal increase affected by the TG length extension before radiation. There exists a high electric field distribution in the overlap area between TG and PPD[8]. With the extension of the TG length, there is a higher chance of having surface and bulk defects and hot-carrier generation due to a high electric field induced impact ionization in that region which will raise the dark current through recombination and thermal generation[5][8].

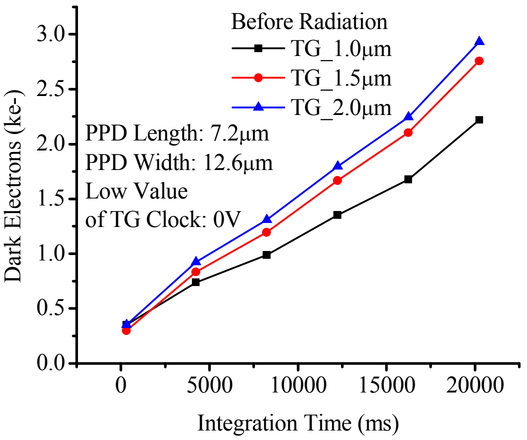

Figure 6. Dark electrons with integration time for different TG length before radiation

However, a longer TG contrarily also poses a lower electric field distribution under the TG and raise the potential barrier, which will make electrons transfer more difficult and bring the dark current down. Thus, the combination of these two effects, gate length extension induced more defects generation and electric field reduction, is the reason that the dark electron in Fig. 6 is not proportionally increasing with the TG length. Meanwhile, the pre-irradiation increase of dark current in Fig.6 is mainly dominated by the TG length extension induced defect and hot-carrier generation[8][10].

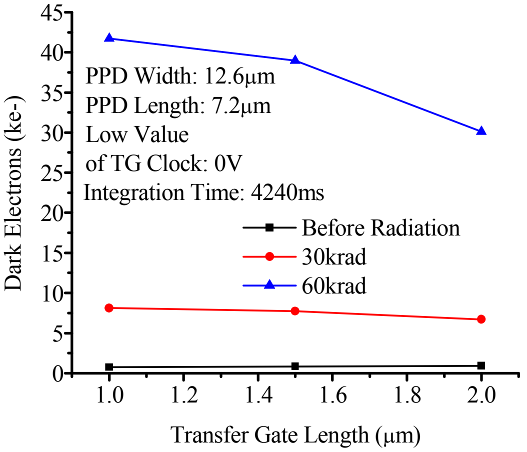

Figure 7. Transfer gate length effect on dark electrons with radiation doses

However, Figure 7 shows that the post-irradiation dark signal goes down with the increasing TG length. Meanwhile, the radiation degradation on the PPD and TG gives an absolute increase of the sensor dark signal due to a lot of radiation induced defect generation and trapped charges in the STI oxide[6].

As mentioned previously, a shorter TG induces a higher electric field under the TG. Taking into account a similar amount of post-irradiation defect generation, a higher electric field will make a higher carrier recombination probability when the same number of defects is generated in that region[10]. Thus, the relative dark signal increase between pre-irradiation and post-irradiation of a longer TG is smaller than that of a shorter TG due to this electric field effect, as it can be seen in Fig. 7. Meanwhile, the post-irradiation dark current is declining with the increasing TG length.

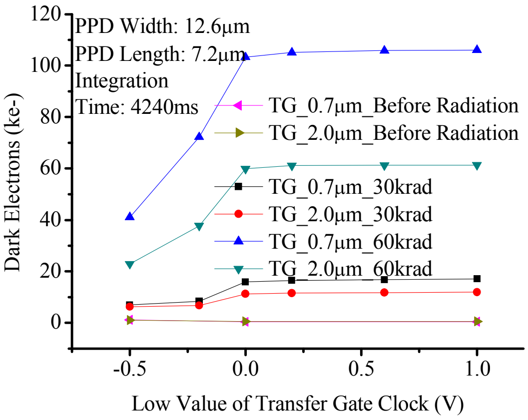

Figure 8. Dark electrons with low value of transfer gate clock voltage before and after radiation for the TG length of 0.7μm and 2.0μm

Figure 8 shows the dark signal variation when changing the low value of the TG clock for two different lengths of TG before and after radiation. With a negative low value of the TG clock, some defects under the TG can be filled by the holes and thus the dark current is reduced. This phenomenon is more obvious with the increasing radiation doses due to more defect fillings[11].

CONCLUSION

In this study, X-ray radiation shows no influence on the PPD pinning voltage because of no post-irradiation trapped charge induced depletion region expansion. Radiation induced dark current increase from the PPD is small and is not proportional to its perimeter due to the pinning layer. The size effect of TG shows a different trend in dark current as a function of TG length before and after radiation. This is due to the pre-irradiation defects creation induced by the TG extension is more dominant over the correspondent electric field reduction, while this situation is reversed after radiation. Moreover, with a negative low value of the TG clock, the holes play an important role to reduce the dark current by defect filling, and this function is getting more effective after radiation.

ACKNOWLEDGMENT

The authors appreciate the involvement of Hans Stouten and Tim Poorter from Philips Health Care to help with the irradiation work on the samples and MESA Imaging for providing the test set-ups.

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